Ambipolar Diffusion and Far-Infrared Polarization from the Galactic Circumnuclear Disk

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ABSTRACT

We describe an implicit prediction of the accretion disk models constructed by Wardle and Königl (1990) for the circumnuclear disk (CND) of gas and dust near the Galactic center: supersonic ambipolar diffusion, an essential dynamical ingredient of the Wardle-Königl disks, will cause the alignment of dust grains due to a process described by Roberge, Hanany, & Messinger (1995). We calculate synthetic maps of the polarized thermal emission which would be caused by ambipolar alignment in the preferred Wardle-Königl model. Our maps are in reasonable agreement with $100\,\mu$m polarimetry of the CND if we assume that the grains have shapes similar to those of grains in nearby molecular clouds and that the CND contains a disordered magnetic field in energy equipartition with its ordered field.

Subject headings: dust — Galaxy: center — infrared: ISM: continuum — ISM: magnetic fields — MHD — polarization

1. INTRODUCTION

The Galactic circumnuclear disk (CND) is a weakly-ionized ring of gas and dust which appears in various types of emission at galactocentric radii $R = 1$–$10\,\mathrm{pc}$ (see Morris & Serabyn 1996 and Davidson 1996 for recent reviews). The origin and structure of the CND magnetic field, $\boldsymbol{B}$, are particularly intriguing: mid- and far-infrared polarimetry (Aitken et al. 1986; Werner et al. 1988; Hildebrand et al. 1990, 1993 [H90, H93]) show that $\boldsymbol{B}$ lies primarily in the plane of the disk and is roughly orthogonal to the poloidal field observed on larger scales. Werner et al. (1988) pointed out that a differentially-rotating disk would deform an initially poloidal field into a predominantly toroidal configuration. Subsequently, Wardle and Königl (1990, [WK]) described self-similar hydromagnetic accretion disk models of the CND; with the addition of a small nonaxisymmetric distortion, the magnetic field predicted by their preferred model, gc2, is in reasonable agreement with the field inferred from far-infrared polarimetry (H93).

In the WK models, the magnetic torques which remove angular momentum from the gas are mediated by supersonic ambipolar diffusion. Coincidentally, Roberge, Hanany, & Messinger (1995, [RHM]) showed that ambipolar diffusion causes grain alignment: the partial coupling of charged dust grains to the drifting field lines produces gas-grain streaming, which causes alignment of the grains via Gold's mechanism (Gold 1952; Purcell 1969; Purcell & Spitzer 1971; Lazarian 1994; RHM). The large magnitude of the "intrinsic" $100\,\mu$m polarization from grains aligned by supersonic ambipolar diffusion (e.g., 20% for oblate silicate grains with 2:1 axis ratios viewed with the most favorable magnetic field geometry; see RHM) leads us to conjecture that the ambipolar mechanism is the predominant cause of grain alignment in the CND. In §§2–3, we test this conjecture by calculating the polarized thermal emission that would be caused by ambipolar alignment in model gc2 and comparing our results to the $100\,\mu$m polarimetry of H90 and H93.

2. CALCULATIONS

The largest optical depth through the CND is < 0.1 at $100\,\mu$m; consequently the Stokes parameters, I, Q, and U, are well described by the transfer equations for optically thin emission,

$$\frac{dI}{ds} = n_d\, B_\nu(T_d)\ (C_{x'} + C_{y'}) \tag{1}$$

$$\frac{dQ}{ds} = n_d\, B_\nu(T_d)\ (C_{x'} - C_{y'})\ F\ \cos 2\psi \tag{2}$$

$$\frac{dU}{ds} = n_d\, B_\nu(T_d)\ (C_{x'} - C_{y'})\ F\ \sin 2\psi \tag{3}$$

(WK90), where s is distance along the line of sight. We integrated equations (1)–(3) to obtain the polarization magnitude, $P = \sqrt{Q^2 + U^2}/I$, and position angle[1], $\theta = \frac{1}{2}\arctan(U/Q)$, using a model of the position-dependent dust density, $n_{\rm d}$, and temperature, $T_{\rm d}$, derived by Davidson et al. (1992) from 50 and $90\,\mu$m photometry of the Galactic center. Our results are only weakly sensitive to uncertainties in $n_{\rm d}$ and $T_{\rm d}$ because the CND is optically and geometrically thin and the FIR emission is in the Rayleigh-Jeans limit. The other variables in equations (1)–(3) are determined by the alignment properties of the grains as follows.

The quantities $C_{x'}$ and $C_{y'}$ are respectively the dust absorption cross sections for light polarized along the $\hat{\boldsymbol{x}}'$ and $\hat{\boldsymbol{y}}'$ directions, where $\hat{\boldsymbol{y}}'$ is parallel to the projection of the local magnetic field onto the plane of the sky, $\hat{\boldsymbol{z}}'$ points toward the observer, $\hat{\boldsymbol{x}}' = \hat{\boldsymbol{y}}' \times \hat{\boldsymbol{z}}'$, and ψ is the angle between $\hat{\boldsymbol{y}}'$ and north, measured counterclockwise from north. To compute $C_{x'}$ and $C_{y'}$, we modeled the grains as oblate spheroids with semiaxes a parallel to the symmetry axis and b $(> a)$ perpendicular to the symmetry axis. We assumed that the angular momentum, $\boldsymbol{J}$, of a rotating spheroid is aligned perfectly with its symmetry axis by the Barnett effect.[2]

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[1]With $\theta = 0$ if the electric vector is polarized along the east-west direction.

[2]That is, we neglected the disalignment of $\boldsymbol{J}$ by thermal fluctuations (Lazarian 1994). This is a good approximation for the conditions of interest here (Lazarian & Roberge 1996).

In this approximation,

$$C_{x'} = C_{\rm avg} + \frac{1}{3} Q_J \left(C_\perp - C_\parallel \right) \tag{4}$$

and

$$C_{y'} = C_{\rm avg} + \frac{1}{3} Q_J \left(1 - 3\cos^2\zeta \right) \left(C_\perp - C_\parallel \right) \tag{5}$$

(Lee & Draine 1985), where $C_\parallel$ and $C_\perp$ are respectively the cross sections for light polarized parallel and perpendicular to the symmetry axis, $C_{\rm avg} \equiv \left(2C_\perp + C_\parallel\right)/3$, and ζ is the angle between $\boldsymbol{B}$ and the plane of the sky. For a given a/b ratio, we computed $C_\parallel$ and $C_\perp$ in the electric dipole approximation using Draine's (1987) dielectric function for astronomical silicates. Notice that P and θ depend only on *ratios* of the grain cross sections, which are independent of grain size in the electric dipole limit. Thus, apart from its weak influence on the grain dynamics (discussed below), the value of b does not affect our calculations. We assumed for simplicity that the grain shape is independent of location and let a/b be a free parameter.

The angles ζ and ψ are functions of the position-dependent disk magnetic field. We computed ζ and ψ from a numerical tabulation of model gc2 kindly supplied by Mark Wardle. The model is self-similar and to determine the hydro variables uniquely it is also necessary to specify the magnetic field, B_0, the density, $n_{\rm H0}$, and the radial (v_{r0}) and azimuthal ($v_{\phi 0}$) velocity components of the neutral gas at some fiducial radius, r_0. We set $r_0 = 1\,$pc and chose $B_0 = 2\,$mG, consistent with H I and OH Zeeman splitting measurements of the CND (reviewed by Morris & Serabyn 1996). We set $n_{\rm H0} = 10^5\,{\rm cm}^{-3}$, near the lower end of the range of estimates for the density (Jackson et al. 1993), and assumed that $v_{\phi 0} = 110\,{\rm km\ s}^{-1}$ and $v_r = -19\,{\rm km\ s}^{-1}$, consistent with kinematic models of the CND (Güsten et al. 1987; Jackson et al. 1993).

The alignment of $\boldsymbol{J}$ with respect to $\boldsymbol{B}$ is characterized by the quantity

$$Q_J \equiv \frac{3}{2}\left[\left\langle \cos^2\beta \right\rangle - \frac{1}{3} \right], \tag{6}$$

where β is the angle between $\boldsymbol{J}$ and $\boldsymbol{B}$ and angle brackets denote the average for all grains. We calculated Q_J from the theory of ambipolar alignment (RHM).[3] For supersonic drift speeds, Q_J depends only on a/b and $v_{\rm d}/v_{\rm th}$, where $v_{\rm d}$ is the gas-grain drift speed and $v_{\rm th} = \sqrt{2kT_{\rm g}/m}$ is the gas thermal speed (RHM). We computed $v_{\rm d}$ at each point using model gc2 to predict the local hydro variables and a prescription for the grain dynamics (Draine 1980) which includes Lorentz and gas drag forces on the grains. For the purposes of calculating the grain dynamics only, we represented the grains as spheres with equivalent radii $r_{\rm eq} = (ab^2)^{1/3}$ and arbitrarily set $b = 0.1\,\mu$m. Changing b by a factor of 2 would have virtually no effect on the calculated polarizations. The WK models do not predict the gas temperature; we set $T_{\rm g} = 300\,$K, consistent with observations of various molecular lines (Harris et al. 1985).

The factor F in equations (2)–(3) represents the possible effects of a random magnetic field component. We set the total field to $\boldsymbol{B}_{\rm avg}+\boldsymbol{\delta B}$, where $\boldsymbol{B}_{\rm avg}$ is the ordered field predicted by model gc2 and $\boldsymbol{\delta B}$ is a random component. We assumed that $\boldsymbol{\delta B}$ is perpendicular to $\boldsymbol{B}_{\rm avg}$ (as would be the case if $\boldsymbol{\delta B}$ is due to Alfvénic turbulence) and that $\boldsymbol{\delta B}$ has an axisymmetric, Gaussian distribution of amplitudes (see Myers & Goodman 1991). For this model, it is straightforward to show that

$$F(\xi) = \frac{3}{\sqrt{2\pi\xi}} \int_0^\infty \frac{e^{-x^2/2\xi}\,dx}{1+x^2} - \frac{1}{2}, \tag{7}$$

where the "turbulence parameter," ξ, is the ratio of the energies in the ordered and disordered field components. We assumed for simplicity that this ratio is independent of position and let ξ be a free parameter. Note that F decreases monotonically from $F(0) = 1$ (no disordered field) to $F(1) \approx 0.5$ (disordered field in equipartition with the ordered field).

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[3]Including Davis-Greenstein alignment would increase Q_J, and hence the polarizations, by an uncertain factor that depends on poorly-known magnetic properties of the grains. The increase would be $\lesssim 40\%$ for grains composed of ordinary paramagnetic substances but could be larger for superparamagnetic grains.

3. Results

We constructed synthetic maps of $P_{\rm thr}$, the 100 μm polarization predicted by ambipolar alignment, for 3,136 parameter combinations sampled uniformly on the intervals $0 < a/b < 1$ and $0 < \xi < 2$. For each $(a/b, \xi)$ combination, we calculated the Stokes parameters on a grid of sightlines uniformly spaced by $1''$ in right ascension and declination. Each map of I, Q, and U was then convolved with a $45''$ (FWHM) Gaussian beam to model the observed resolution (H93) and maps of $P_{\rm thr}$ were computed from the convolved Stokes parameters. Optimal values of a/b and ξ were obtained by performing a χ^2 fit to $P_{\rm obs}$, the 100 μm polarization observed along $N = 23$ lines of sight (H90, H93). Our fits omitted 7 observed sightlines for which the FIR emission is not associated with the CND. We did not attempt to fit θ, which is a good diagnostic of the magnetic field geometry but not of the alignment mechanism.

Strictly speaking, the value of $P_{\rm obs}$ we calculate for each sightline is the *mean* polarization for a hypothetical ensemble of disks with identical distribution functions for $\boldsymbol{\delta B}$. That is, discrepancies between $P_{\rm thr}$ and $P_{\rm obs}$ are due not only to uncertainties in our theoretical model but also to random fluctuations in $\boldsymbol{B}$. To include the effects of random fluctuations on χ^2, we assumed that the polarization observed along the ith sightline has dispersion $\sigma_i^2 = \sigma_{{\rm obs},i}^2 + \sigma_{\rm trb}^2$, where $\sigma_{{\rm obs},i}$ is the observational uncertainty quoted by H93 and $\sigma_{\rm trb}$ represents the uncertainty due to fluctuations in $\boldsymbol{B}$. We assumed for simplicity that $\sigma_{\rm trb}$ is the same for every sightline and performed the χ^2 fits independently for different choices of $\sigma_{\rm trb}$. We found that χ^2 per degree of freedom is ≤ 1 in some subset of parameter space if $\sigma_{\rm trb} \geq 0.6\%$. That is, we are able to obtain a reasonable fit to the data if we assume that the random fluctuations in $P_{\rm obs}$ are about half a percent.[4]

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[4]This logic probably overestimates $\sigma_{\rm trb}$, since some of the errors that are ascribed to fluctuations in $P_{\rm obs}$ are undoubtedly due to idealizations in our model. For example, H93 pointed out that the WK models predict polarizations that are symmetric in the northwest

Figure 1 is a contour plot of χ^2 per degree of freedom (χ^2/ν) for the case $\sigma_{\rm trb} = 0.6\%$. Evidently the observations are consistent with a continuum of models with different combinations of a/b and ξ; this is due to the fact that a small increase in a/b (which tends to reduce $P_{\rm thr}$) can always be compensated by a decrease in ξ (which tends to increase $P_{\rm thr}$). Thus, the contours of constant χ^2/ν slope downward with increasing a/b. It is interesting to note that the parameters allowed by our fits are consistent with independent constraints: For example, observations show nearby molecular clouds have $\xi \approx 1$ (Jones 1989; Myers & Goodman 1991). Also, Zeeman splitting observations of the 21 cm HI (Schwarz & Lazenby 1990) and 18 cm OH (Killeen et al. 1993) lines toward the Galactic center imply that the magnetic energy density of the CND is comparable to the turbulent energy density inferred from atomic and molecular linewidths (Güsten et al. 1987; Jackson et al. 1993). These observations are consistent with the presence of nonlinear Alfvén waves in the CND, for which $\xi \approx 1$. Nonlinear Alfvén waves are predicted by some models of magnetic braking (Mouschovias & Morton 1985). Similarly, photopolarimetry of the 9.7 μm silicate resonance implies that the aligned grains in nearby molecular clouds are oblate with $a/b \approx 2/3$ (Hildebrand & Dragovan 1995). A model with $a/b = 2/3$ and $\xi = 1$ (indicated by the filled circle in Fig. 1) is compared with the observations in Figure 2. For this model, $\chi^2/\nu = 0.97$ and the mean discrepancy between $P_{\rm thr}$ and $P_{\rm obs}$ is -0.2%.

Our results are insensitive to the precise values of the hydrodynamic variables; for example, the polarizations we calculate would be virtually identical if we arbitrarily increased or decreased $n_{\rm H}$ or B by factors of ~ 3. This robustness is due to the fact that, for the highly supersonic drift speeds in the WK models ($v_{\rm d} \gtrsim 10\, v_{\rm th}$ for gc2), the efficiency of ambipolar

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and southeast quadrants. However, the observations clearly show departures from symmetry in the southeast quadrant; not surprisingly, these points contribute about twice as much on average to χ^2 as the rest of the data.

alignment saturates at a value which depends only on the grain shape (see RHM, Fig. 12). However, our results *are* sensitive to the magnetic field geometry. For example, we attempted to fit the observations by arbitrarily replacing the magnetic field predicted by model gc2 with a purely toroidal field of the same magnitude at each point; we were unable to find solutions with $\chi^2/\nu < 2$ for these models. It will be interesting to see whether one can model the CND observations successfully with more detailed hydro models (e.g., Wardle & Königl 1993) which calculate the vertical structure of the disk.

Previous models of the CND magnetic field geometry (WK, H90, H93) have accounted successfully for the observed polarization position angles by assuming that the efficiency of grain alignment is independent of position. The saturation of ambipolar alignment at large drift speeds provides a natural justification for this assumption. In contrast, it is difficult to reconcile the uniform efficiency required by the observations with other alignment mechanisms. If the grains are superparamagnetic, then the efficiency of Davis-Greenstein alignment would be saturated but the saturation efficiency would be very sensitive to the local dust-to-gas temperature ratio: independent calculations on DG alignment (Lazarian 1995) show that factor of 2 variations in T_d/T_g would cause factor of ≈ 3 variations in $\langle \cos^2 \beta \rangle$. The efficiency of Purcell's mechanism (Purcell 1979) is insensitive to $T_{\rm d}/T_{\rm g}$ but sensitive to the timescale for changes in the grain surface properties; it is difficult to see why the latter should be uniform throughout the CND and have just the right value to reproduce the observations. We conclude that the degree and uniformity of the alignment required by the observations are natural consequences of ambipolar alignment but difficult to explain with other mechanisms.

4. SUMMARY

1. We have calculated the 100 μm linear polarization from the CND using a model that attributes the grain alignment to ambipolar diffusion in the Wardle-Königl model accretion disks. Our polarization maps depend on just 2 adjustable parameters, the grain axis ratio, a/b, and the mean ratio, ξ, of the energies in the random and ordered magnetic field components.

2. We estimated the values of a/b and ξ by performing a χ^2 fit to the observed 100 μm polarizations (H90, H93). Our models provide a reasonable fit to the observations if we assume that the 1σ fluctuations in the observed polarizations due to turblence in the CND are $\geq 0.6\%$.

3. The observations are consistent with a continuum of models with different $(a/b, \xi)$ values. A model with $a/b = 2/3$ and $\xi = 1$, the parameter values implied by independent constraints, falls close to the minimum of χ^2 per degree of freedom. For this model, $\chi^2/\nu = 0.97$ and the mean error in the predicted polarizations is -0.2%.

4. Our calculations imply that grains in the CND must be aligned with an efficiency such that $\langle \cos^2 \beta \rangle \approx 0.5$, nearly independent of position. The degree and uniformity of alignment required by the observations are natural predictions of the ambipolar mechanism but require "fine tuning" of the parameters in other alignment theories.

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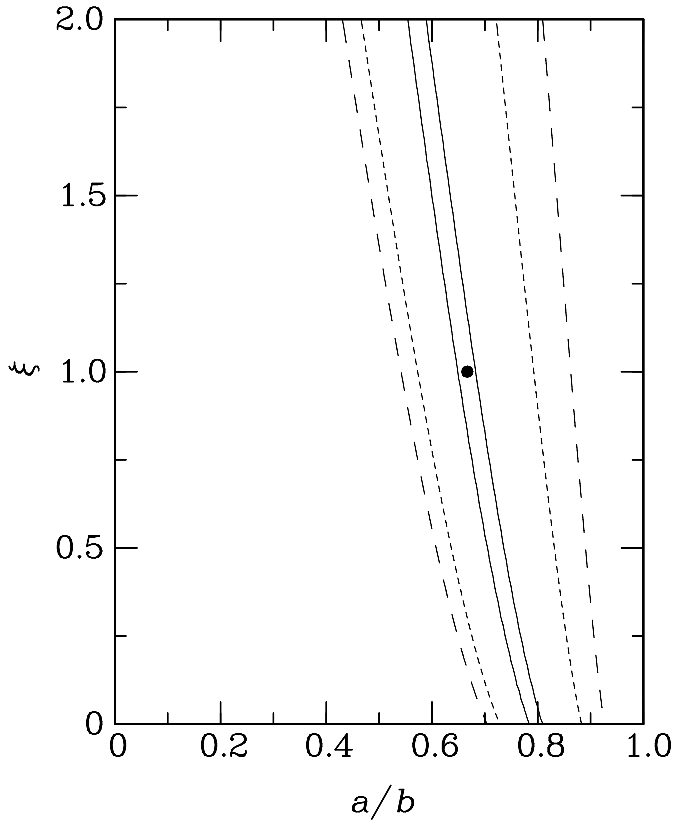

Fig. 1.— Contours of $\chi^2/\nu = 1$ (solid lines), 2 (short dash), and 3 (long dash) determined by fitting the grain axis ratio, a/b, and turbulence parameter, ξ. The filled circle marks the point $(a/b, \xi) = (2/3, 1)$ (see text).

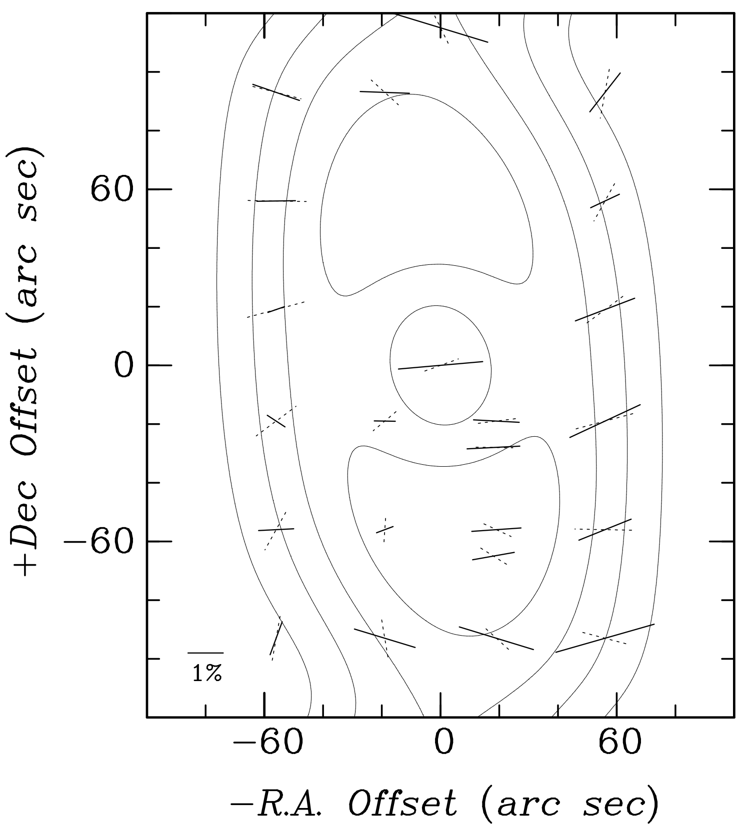

Fig. 2.— Comparison between the far-infrared polarizations observed toward the CND (solid lines) and the predictions of a model with $(a/b, \xi) = (2/3, 1)$ (dashed lines). Also shown are contours of the 100 μm intensity predicted by our model, with contours at 20%, 40%, 60%, and 80% of the peak intensity. Offsets are measured from $\alpha = 17^{\rm h}42^{\rm m}29\overset{\rm s}{.}4$, $\delta = -28°59'19''$ (1950).